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# Using mixed-method analytical historical ecology to map land use and land cover change for ecocultural restoration in the Klamath River Basin (Northern California)

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ABSTRACT

Ecocultural restoration involves the reciprocal repair of ecosystems and revitalization of cultural practices to enhance their mutual resilience to natural and anthropogenic disturbances and climate change stressors. Resilient ecocultural systems are adapted to retain structure and function in the face of disturbances that remain within historical ranges of severity. To assist in ecocultural restoration and management, understanding how a system has historically responded to different types of disturbances is therefore invaluable in understanding how social-ecological resilience can be maintained in the face of future stressors and disturbances. However, records of disturbances and ecocultural responses can be limited for certain landscapes and human communities. In this methods paper, we demonstrate a mixed-method process for integrating oral history, field-based knowledge, archival information, and historical and contemporary aerial images to gain insight into the changes on the Klamath River in Northern California from the 1940s through 2020. We georegistered historical imagery, quantified changes between land cover classes, and contextualized these classifications with qualitative assessments of changes in larger surrounding areas. By synthesizing these data sources with field measurements, mining and other land survey maps, timber management plans, fire and flood histories, and interviews with members of the Karuk Tribe, we were able to reconstruct the land use and land cover change histories at five sites. We noted that recovery of canopy cover from fire and logging practices was faster than for flood, which was faster than recovery from mining, consistent with the relative severity of likely soil disturbance. By combining different sources of information with complementary strengths, we were able to provide managers with site-specific information on recovery from different types of disturbance. Though this approach was labor-intensive, with emerging tools for supervised classification of high-resolution imagery, mixed-method analytical historical ecology could be applied more broadly, supporting ecocultural restoration on a larger scale.

## 1. Introduction

In this paper, we demonstrate a mixed-methods, interdisciplinary historical ecology reconstruction of land use, land cover and management in the Klamath River Basin. We take an analytical approach to historical ecology in order to inform the eco-cultural restoration goals of the Karuk Tribe (Tribe) as they steward the landscape, working to enhance social-ecological resilience to natural and anthropogenic disturbances and climate change stressors. We begin with background on ecocultural restoration, resilience theory, and historical ecology.

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### 1.1. Ecocultural restoration

The paradigm of ecocultural restoration emphasizes the active role of Indigenous people in dynamically stewarding and repairing ecosystems and the reciprocal relationships between human and non-humans in ecosystem management and rehabilitation (Diver et al., 2019; Kimmerer, 2011; Pearce, 2019). Ecocultural approaches to restoration center Indigenous connections to place as well as community capability and decision-making in reinforcing and building Indigenous peoples' resilience (Eitzel et al., 2021; Pearce, 2019). In the context of Karuk cultural food systems, a range of cultural practices were developed over millennia and across generations to manage habitats and ecosystems for a plethora of cultural use species assemblages across unique habitat types, along with a cultural land management ethic that prioritized reciprocal stewardship of all species and associated ecosystem functions and dynamics across the landscape (Karuk Tribe Department of Natural Resources, 2010; Sowerwine et al., 2019c). Drawing from that ethic, the research presented in this paper is grounded in the Karuk Tribe's current ecocultural restoration goals in the Klamath River Basin. These goals include rehabilitating ecosystems at the landscape scale not only for ecological resilience to disturbances and climate change, but also for socio-cultural resilience, culturally important plant and animal species, human health and wellbeing.

Restoring biodiverse landscapes and revitalizing cultural connections to place both entail piecing together the complex and intertwined histories of management and land and water use, as well as ecosystem responses to anthropogenic and natural disturbances across space and time (Mansourian et al., 2020). Key to implementing cultural management prescriptions and furthering eco-cultural revitalization goals (particularly for culturally significant sites) is understanding how different waves of resource management strategies impacted land use patterns – and in turn how ecosystems responded to different forms of natural and anthropogenic disturbances.

### 1.2. Ecosystem resilience to disturbance

Theories of ecosystem and sociocultural-ecosystem stability have changed over the years. The equilibrium paradigm that depicted ecosystems as systems that return predictably along a successional trajectory to an equilibrium or a single stable state began to unravel in the 1960s (Clements, 1916; Gunderson, 2000; Scoones, 1999). In its place, a new conceptual language describing the behavior of ecosystems as complex adaptive systems with non-linear and emergent dynamics "operating at some distance from equilibrium" was developed (Holling, 1973; Patten and Odum, 1981). Recent theories conceptualize ecosystems as assemblages of organisms and abiotic processes that self-organize and respond to multiple sources of disturbances across numerous spatial and temporal scales, cycling between multiple states of variable stability (Angeler and Allen, 2016). The plant and animal species that characterize ecosystems adapt to specific ranges of disturbances, such as fires, floods, landslides, and droughts. Disturbances of uncharacteristic size, intensity, magnitude and frequency can transition ecosystems across thresholds into other states of organization which have a completely different set of biotic and abiotic relationships (Walker and Salt, 2006). Changes to ecological system function and components directly impact the cultural practices, relationships, and processes that were formed over millennia and generations, to novel and potentially maladaptive configurations not fully represented in the past. This complicates or hinders current and future socio-cultural adaptive capacities.

These framings focus ecosystem stewardship paradigms on managing for resilience of complex social-ecological systems. In ecological management, the definition of "resilience" is the "persistence of relationships within a system and measure of the ability of these systems to absorb changes" (Holling, 1973), maintaining their structure and function (Quinlan et al., 2015). The concept of resilience is also prominent is used n the literature on coupled social-ecological systems to describe (i) the amount of disturbance that a social-ecological system can absorb and still remain within a particular state or configuration of relationships; (ii) the capacity of a system to learn and adapt; and (iii) the degree to which the system is capable of self-organizing (Carpenter et al., 2001). Karuk stewardship, as both socio-cultural process and management influence, historically enhanced the resilience of the Klamath social-ecological system by buffering landscapes against climatic and ecological stressors such as droughts, floods, landslides and fires. Plant and animal biodiversity, forest stand and structure and landscape heterogeneity of the Klamath were stewarded to withstand periodic disturbances, such as fires or pest outbreaks, within particular ranges and frequencies. Karuk stewardship also has the potential to support contemporary adaptive capacity of forest ecosystems in the Klamath Basin in the face of uncharacteristic ranges, sizes, frequencies and dynamics of disturbances such as fires, droughts, extreme heat, floods and uncertainty in the timing and amount of precipitation, which will put additional stress on ecosystems and communities (Karuk Tribe, 2019). Social and ecological resilience can mutually reinforce each other when the ecological characteristics (e.g. species diversity, habitat quality and ecosystem function) support cultural practices which sustain Indigenous people and relationships, and vice versa. In this paper, we focus largely on ecological characteristics (for example, gaps in woody cover or tree canopy), but these characteristics are proxies or indicators of the potential for cultural support via the health and diversity of understory plants which often have important cultural uses and relationships.

To manage for social-ecological and ecocultural resilience on the ground and in real-time, it is critical to both understand and characterize the multiple sources of disturbance and stressors in a particular system, as well as study their impact on ecosystem composition and structure over space and time. If indeed some species assemblages are adapted for a certain level of disturbance, managers need to know what threshold of stressors is so severe that a system will not recover and may shift into an alternative state. To this end, historical ecology can be an invaluable way to characterize a range of past disturbances in a landscape to inform management that can enhance cultural ecosystem services (Mucioki et al., 2021).

### 1.3. Quantitative and qualitative historical ecology

Historical ecology is a well-established discipline, with multiple techniques for reconstructing prior landscapes (Beller et al., 2016; Grossinger et al., 2007), quantitative histories of abundance and extent of ecosystems and species (Scarborough et al., 2022; Thurstan et al., 2020; Zu Ermgassen et al., 2012), and environmental risks (Hester, 2019). Techniques range from archeology, paleontology (e.g. pollen records), dendrochronology, and archival work, as well as geospatial analysis of historical aerial photographs and maps (Egan and Howell, 2001, Vellend et al., 2013, Santana-Cordero and Szabo, 2019, Szabó et al., 2017). Though historical ecology and ecological modeling can be mutually complementary in supporting ecosystem management (Gimmi and Bugmann, 2013) by informing studies of land cover change, most reconstructions built from historical aerial imagery and archival records only quantify total cover type (Beller et al., 2016; Grossinger et al., 2007) and less often quantify change from one cover type to another (but see Van Dyke and Wasson, 2005, Amici et al., 2017, Baumgarten, 2021). Integrating quantitative and qualitative methods in order to reconstruct cover change over time has the potential for a richer understanding of ecosystem shifts and can offer a way to integrate different kinds of knowledge.

A key source of information for these reconstructions is historical aerial imagery. Manual photo interpretation can be labor-intensive (Morgan et al., 2010), and therefore some studies have used automated or semi-automated classification methods to improve the efficiency of classifying historical aerial imagery (e.g. Baatz and Schäpe, 2000; Drăguţ et al., 2014; Eitzel et al., 2016; Whiteside et al., 2020).

These methods have their own issues, however, requiring expert knowledge of prohibitively expensive software. Because of these limitations, manual delineation within a geographic information system (GIS) relying on traditional aerial photo interpretation (Blaschke, 2012) is still common and has relatively low barriers to entry. Although this method is not automated, humans with specific training have an innate ability to cognitively differentiate tones, texture and spatial arrangements of pixels and relate these patterns into image-objects representing land cover features within their geographic contexts (Hay et al., 2003). Moreover, individuals such as local Indigenous people who hold expert knowledge of a landscape's ecology have a particular advantage in classifying features in historic imagery. With a small number of generalized classes, manually digitized at a fine scale resolution, a high level of confidence can be attributed to classified historical imagery (Zhang, 1996). If the historic imagery is carefully georegistered to invariant control points, identifiable in contemporary orthorectified imagery, size and range shifts of the land cover classes can be compared with higher confidence for descriptive change detection analysis.

Paired with interviews and archival research, manually classified historical imagery can contribute to the construction of timelines of change for different sites which can then be compared (Santana-Cordero and Szabo, 2019). Most importantly, taking a historical ecology approach allows verification (if not quantitative validation) of the historical imagery using other lines of evidence. Applying mixed-methods techniques including qualitative interpretations of disturbances alongside quantitative measurements can allow us to derive rich information on ecosystem responses to varied historical disturbances – supporting ecocultural restoration goals.

### *1.4. Analytical historical ecology on the Klamath*

The Karuk Tribe has recently engaged in a multifaceted research and monitoring program to better understand cultural agroecosystem resilience through a mixed-method approach grounded in Indigenous and Western science methods (Karuk Tribe-UC Berkeley Collaborative, 2023). A key element of this project includes land use and land cover change detection. The Tribe's investment in research and deep knowledge in this region of California with rich historical data makes the Klamath an ideal system to demonstrate the potential of analytical historical ecology for ecocultural restoration objectives. These methods can help Indigenous managers and allies understand 1) how culturally important species and their associated habitats are impacted by different types of climatic stressors and socio-ecological disturbances at different spatial and temporal scales, 2) how these species and habitats respond to and recover from disturbances, and 3) how well management prescriptions accomplish restoration or revitalization goals over time and across the landscape at different scales. For the Karuk Aboriginal Territory, there are sparse written archival records on historical land use, management, and vegetation conditions, although there exists an abundance of orally transmitted information among the local Indigenous community. We emphasize that though we focus in this study largely on a narrow period of time for which aerial imagery is available (1944–2020), these lands have been stewarded by the Karuk Tribe for millenia (Salter, 2003). Our community partners' Indigenous science and cultural knowledge traditions are grounded in this long term relationship and extend far beyond the period for which written records and especially aerial imagery exist (Knight et al., 2022).

As we demonstrate in this paper, ecocultural restoration can benefit from all available information through Indigenous-led, community-engaged and mixed methods approaches. Our methods paper shares specific approaches to combining high resolution aerial imagery with archival and interview research in order to piece together trends in land cover change – demonstrating ecosystem responses to multiple forms of disturbance over multi-decadal time scales (focusing on 1944–2020). We take a fine-grained, local approach to manual image processing and classification, producing high-quality analysis for individual study sites which we combine with narrative and qualitative assessment of the images. Using this method, we reconstructed the recent land use and land cover change history of several Karuk Tribal research sites in the Klamath River Basin in northern California. We also quantified the ecosystems' recovery from fire, flood, and forestry management at several of these sites, and contextualized our conclusions with a broader qualitative assessment of the areas surrounding the study sites.

## 2. Materials and methods

This work is a collaboration between university and federal agency researchers and Karuk Tribal staff and Tribal members/descendants/cultural practitioners (see Appendix A for details on researcher roles and positionality). Table 1 details the specific steps in our mixed-methods historical ecology approach to reconstructing land-use history/land cover change.

**Table 1**
Workflow for our mixed-methods historical ecology approach to reconstructing land-use history/land cover change.

| | |
|---|---|
| Step 1: Locate imagery and collect land-use history | — Archival research to locate high-resolution historical and recent imagery; mining, logging, and homesteading records; and fire and flood histories for study areas<br>— Interviews, focus groups, and site visits with Karuk Tribal members/descendants/cultural practitioners to reconstruct historical and contemporary use and management<br>— Identify locations based on recent georegistered images and GPS coordinates |
| Step 2: Georegister historical imagery | — Manually identify Ground Control Points and use smoothing splines to warp image appropriately |
| Step 3: Segment and classify imagery | — With two analysts, discuss each image with reference to recent field experience of the sites and known land use history as well as known aspects of these image types<br>— Manually draw shapes and assign classes<br>— Possibly repeat Step 3 based on analysts' improving knowledge of the sites and the imagery, e.g. correcting an earlier classification after noting features from a later image |
| Step 4: Assess uncertainty and validate classification | — Measure GPS uncertainty and georegistration uncertainty<br>— Compare independent classifications against ground truth data for recent imagery using Kappa accuracy, and compare inter-rater reliability between independent classifications using Krippendorff's Alpha |
| Step 5: Visualize and analyze change | — Construct a timeline of major land-use/management events<br>— Summarize total area change of each class over time<br>— Rasterize the classification, and use R package 'ggalluvial' to show pixel-by-pixel change between classes<br>— For known disturbances, select images capturing the trajectory of recovery and calculate annual change in area of canopy cover |
| Step 6: Examine broader landscape | — To check interpretations of reconstructed change at local field sites, examine image series showing evolution of larger surrounding landscape over time (based on new insights, return to Step 5 as necessary, especially the timeline) |
| Throughout (especially Steps 1, 3, and 5): Iterative feedback with community members | — Feedback on methods over virtual and in-person meetings<br>— Iterative review of results and adjustment of land-use timelines and interpretations based on community comments (based on insights, return to step 5 as necessary, especially the timeline)<br>— Co-Authorship of reports and publications |

### 2.1. Study system and site selection

#### 2.1.1. The Klamath River and the Karuk people

The Klamath River flows from the Cascade Mountain Range in Southern Oregon to the Pacific Ocean in Northern California; the aboriginal territory of the Karuk Tribe is in the middle stretch of the Klamath River Basin (Fig. 1). Due to its legacy of Indigenous stewardship and its unique geologic, hydrologic and ecological conditions, the Klamath River Basin supports some of the most biologically diverse ecosystems in the United States. (Della Sala et al., 1999; Sawyer, 2007, Kaufmann and Garwood, 2022; Olson et al., 2012). Karuk people have inhabited the middle section of the Klamath Basin for millennia and steward its landscapes for cultural use species including those used for food, fibers, basketry materials, and medicines (Karuk Tribe Department of Natural Resources, 2010; Noorgard, 2005; Salter, 2003; Sowerwine et al., 2019a).

However, the cumulative impacts of fire exclusion, logging, mining and ranching over the past century have resulted in widespread ecosystem degradation and a decline in access to culturally important species that are vital to the health and well-being of Karuk people (Karuk Tribe, 2019; Sowerwine et al., 2019b). Following the ecological and cultural destruction of the fur and gold rushes of the 19th Century, what was the Klamath Forest Reserve became National Forest in 1905, followed by the Six Rivers National Forest in 1947, resulting in widespread fire exclusion coupled with extensive logging and replacement of diverse mixed conifer, hardwood, oak woodlands and meadows with even-aged Douglas-fir and pine plantations. Throughout the 20th century, USFS managers suppressed and excluded fires and criminalized traditional practices such as cultural burning, fishing, hunting, and gathering of many resources (Diver et al., 2019; Lake, 2007; Noorgard, 2005; Sarna-Wojcicki et al., 2019). Additionally, decades of illicit cannabis grows accompanied by copious fungi-, herbi-, and pesticide application, as well as climate change, pose further compounding threats and are stressor agents to the unique biological diversity and Indigenous cultural uses of resources within Karuk Aboriginal Territory (Karuk Tribe, 2019). The Karuk Tribe regained federal recognition in 1978, and today exercises sovereignty over nearly 4000 enrolled members and their 1.4 million acre Aboriginal territory. Over the past three decades, the Karuk Tribe Department of Natural Resources (KDNR) has been working to restore the ecosystems of their territory, revitalize cultural use species and (re) connect Karuk people to place (Karuk Tribe, 2019; Karuk Tribe Department of Natural Resources, 2010; Lake et al., 2010).

#### 2.1.2. Study site selection for land use and land cover mapping

In support of the Tribe's climate adaptation and ecocultural revitalization goals, the Karuk-UC Berkeley Collaborative launched the "Karuk Agroecosystem Resilience and Cultural Foods and Fibers Revitalization Initiative: *xúus nu'éethti* – we are caring for it" from 2018 to 2022 (Karuk Tribe-UC Berkeley Collaborative, 2023). The project focused on 10 acre-sized plots that represented culturally significant sites with diverse food, fiber, regalia and/or medicinal plants, were inclusive of habitat delineations included in the Karuk Climate Adaptation Plan and Vulnerability Assessment (Karuk Tribe, 2019; Karuk Tribe Dept. of Natural Resources, 2016), covered a range of elevations (<1500, 1500–2500, >2500 ft), were accessible, included diverse water bodies, overlapped with other data collection efforts, and were prioritized by KDNR for management. Of these sites, 5 were chosen for in-depth research on long-term changes in land use, management and cover over time. These 5 sites were selected because they have relatively complete historical datasets on land use and cover and rich living community knowledge about historical and recent land management and ecosystem response. All sites in this study, including the 5 chosen for in depth land use/land cover change detection, were located with GPS (Garmin eTrex 22x) and surveyed using a co-produced protocol that included line intercept and relevé methods from the Fire Effects Monitoring and Inventory System to capture forest, shrub, and herbaceous cover and plant species frequency and diversity (Lutes et al., 2006). We also gathered information on land use history via interviews and archival research. This field knowledge underlies our ability to validate the classifications of contemporary images, and the land use history informs our classifications of historical imagery.

### 2.2. Interviews and archival research

Through semi-structured in-depth interviews, focus groups and site visits with KDNR managers and cultural practitioners connected to and knowledgeable about the sites, we gathered data on the historical and contemporary use, condition and management of the land, water and cultural use plant species of these five sites.[1] Focus groups were conducted on and off-site with cultural practitioners, Tribal managers and academic and Federal agency scientists over the course of the Initiative. In-depth interviews were conducted with nine cultural practitioners and Tribal managers (including authors Kathy McCovey, Lisa Morehead-Hillman, Leaf Hillman, Chook-Chook Hilman, Frank Lake, Vikki Preston and Bill Tripp). Information about both historic and contemporary Karuk cultural use and management as well as settler-colonial land and water management (including fire exclusion, logging, mining and homesteading in and around the plots) was gathered through research in archival records (see Appendix A for more details). Based on information synthesized from archival information, interviews, and focus groups, we constructed timelines for each site representing major events and land use changes including forestry operations, fires, and floods as well as timing of rematriation of some of the sites to the Tribe. As we constructed the image series we consulted the timelines and underlying qualitative information to elaborate on certain processes visible in the images, and we asked practitioners and managers to reflect on observations we had made about land-use changes based on the images – adjusting timelines and interpretations to incorporate their feedback.

### 2.3. Image processing

We used QGIS version 3.22.4 (QGIS.org, 2022), for georegistration, classification, and rasterization, and R version 4.2.0 (R Core Team, 2022) for validation calculations, analysis, and visualization of figures. Historical aerial image frames were located at university libraries (UC Berkeley and UC Santa Barbara map libraries) and other agencies (e.g. California Geological Survey in Arcata). National Agricultural Imagery Program (NAIP) quarter-quads were downloaded from the California Natural Resources Agency's GIS archive (2005–2016); NAIP for 2018 and 2020 was retrieved via ArcGIS basemap layers. We used QGIS' georegistration tool with a set of persistent features in the landscape to georegister the images and a separate set of persistent features to assess the spatial accuracy of the georegistration. See Appendix A for detailed protocols and Appendix B for spatial accuracy measurements.

### 2.4. Image classification and validation

#### 2.4.1. Classification scheme and methods

We created a polygon that would contain key points from the field plots, and within this polygon, two analysts (M.V. Eitzel, MVE and Daniel Sarna-Wojcicki, DSW) discussed and agreed on visual interpretation of each image and manually drew polygons and classified them as "non-canopy," "canopy," or "road." The differentiation between "non-canopy" and "canopy" is a significant distinction in contemporary Klamath landscape ecology because timber plantations and fire suppression have resulted in rapid conifer encroachment and meadow reduction over the last century (Cocking et al., 2012; Eitzel et al., 2015). Canopy

[1] Research complied with both UC Berkeley's IRB protocol for the protection of human research subjects (CPHS # 2021–08-14,604), as well as the Karuk Tribe's Practicing Pikyav Tribal oversight research protocol.

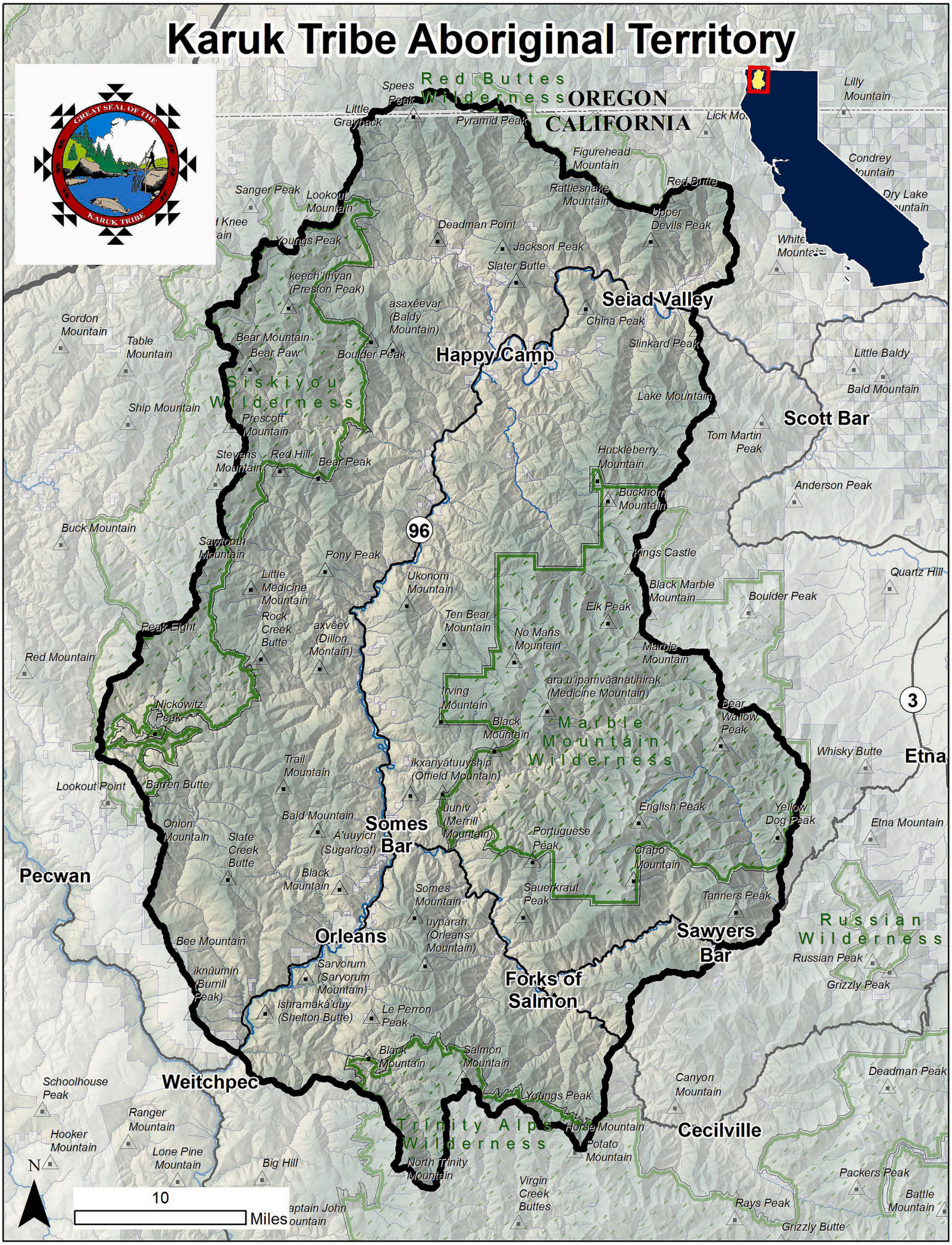


**Fig. 1.** Karuk Tribe Aboriginal Territory. Source: Jill Beckman in Sarna-Wojcicki et al., 2019.

openings support habitat conditions for cultural plants including hardwoods, shrubs and herbaceous species, and therefore analyzing their dynamics over space and time is a culturally and ecologically important focus for classification efforts. We distinguish conceptually between canopy and non-canopy by assuming that 'canopy' is vegetation taller than approximately two feet - likely to be shrubs and trees, while 'non-canopy' is shorter, likely to be herbaceous (grasses and forbs) but could include bare ground, duff, burnt vegetation, and small shrubs and tree seedlings/saplings that are short enough to blend in with the herbaceous species. Though this classification is relatively coarse, the analysts could consistently make these distinctions for all sites and images, despite great variation in quality and interpretability from image to image (due to image characteristics such as color vs black-and-white, pixel size, shadows, panoramic distortion, and blurriness).

"Non-canopy" was largely determined by its light colors and fine, consistent texture. "Non-canopy" that was likely to be bare ground was very bright in most images while burnt vegetation was typically blue in false-color images. "Canopy" was often darker and less consistent in texture, with deeper shadows reflecting varying vegetation height. The distinction between bare ground (included in "non-canopy") and "road" depended on "road" having a consistent width and relatively smooth, straight sides, as well as a judgment on the part of the analysts that the road was likely in use for vehicular or foot traffic. MVE and DSW classified all images for all sites from 1944 through 2018. In the discussion, we also describe other classification schemes that we explored, evaluating the tradeoffs between simplification for comparative analysis and richness of representation for specific sites.

#### 2.4.2. Classification validation

To validate our methods, we assessed the accuracy and reliability of the classification for the 2020 imagery (for which we had access to ground truth information). To assess accuracy for the 2020 classifications, authors M.V. Eitzel (MVE) and Sean Hogan (SH) each independently classified the 2020 NAIP imagery using the methods summarized here and detailed in Appendix A. Author Daniel Sarna-Wojcicki (DSW) had conducted ground-based surveys in the research plots in 2020 and could therefore ground-truth these classifications. SH generated a stratified random sample of points across all five sites (Stehman, 1996), resulting in 7437 total points. DSW classified each of the points based on his knowledge of the field sites. We then calculated kappa for both MVE and SH's classifications, to assess the accuracy of each compared to DSW's field-based knowledge (Lillesand et al., 2015; see Supplemental Information for R code). Finally, we calculated Krippendorff's Alpha (Krippendorff, 2013) as a measure of inter-rater reliability between SH and MVE, using the "kripp.alpha" function in the "irr" package in R (Gamer et al., 2019). We used the 'boot' function in R to calculate 1000 bootstrap samples in order to get a confidence interval. We also compared the absolute differences in area of the different classes classified by SH and MVE, in order to evaluate the potential impact on other quantifications based on the classified areas.

### 2.5. Analyzing land use and land cover change

#### 2.5.1. Proportion over time plots and alluvial plots

To summarize land-cover change, we summed up the area of all the polygons of each land cover type in each year and plotted the change in proportions of each class over time for each site. We also rasterized the classifications (with a pixel size equal to the spatial resolution of the coarsest image for that site), and used "alluvial" plots that group pixels by class and trace the transitions of each pixel from one class to another over time (using the package "ggalluvial" in R; Brunson and Read, 2020).

#### 2.5.2. Calculating recovery rates of "canopy" cover

To assess the rate of regrowth of "canopy" cover, we selected sets of two or more images that followed a disturbance known from the interviews and archival research, and calculated the average area per year that the "canopy" class increased following that disturbance. Interpreting change in canopy cover as a measure of recovery relies on the assumption that no additional management or disturbance occurred during the interval between images. For example, at *Tishánik*, there was a fire in 2013, NAIP images in 2014 and 2016, and then additional prescribed fires following that. Therefore we could calculate recovery from 2014 to 2016 of canopy cover in hectares per year. Where multiple images captured a trajectory of recovery, we calculated both 'instantaneous' rates between pairs of images, and also an overall average recovery rate from the earliest image post-disturbance to the latest image before a new disturbance occurred (or until the canopy cover reached 100% of the plot area). This resulted in seven such events: four sites recovering from logging practices of various types, two recoveries from fire, and one recovery from flood.

#### 2.5.3. Qualitative assessment of landscape change surrounding sites

To complement the fine-scale detail at our plots and to check the conclusions of the quantitative analysis above, we examined larger areas that encompassed our field sites, reconstructing the broader land-use and land-cover changes that occurred around them. In some cases, we were able to corroborate these larger areas' histories with details from archival research that we had been unable to connect conclusively to the smaller areas of our field plots.

## 3. Results

See Appendix B for a list of images, pixel sizes, and imagery types, and a list of uncertainty measurements in different stages of our process.

### 3.1. Classification validation results

The kappa value from comparing Daniel Sarna-Wojcicki (DSW)'s ground truth validation points with M.V. Eitzel (MVE)'s 2020 classification was 0.84 (confidence interval: 0.82,0.86) and from comparing with Sean Hogan (SH)'s 2020 classification was 0.74 (0.71,0.76), which is consistent with a collaborator who worked more independently. Based on Jensen (2005), kappa >80% indicates strong agreement, and 40–80% indicates moderate agreement.

The Krippendorff's Alpha from comparing MVE and SH's classifications with each other was 0.68 (0.65–0.71). Based on Krippendorff (2013), Alpha between 0.67 and 0.80 should only be used to draw tentative conclusions. Given the subjective nature of manual photointerpretation, we take this result to mean that the agreement is at the low end of being good enough to draw conclusions about land cover change. Differences between the two classifications in terms of absolute area for each site were as follows: for Kámmaahriv, SH classified 0.061 ha more canopy cover than MVE; for Táasich, 0.028 more; for Tishánik 0.107 more; and for Lower Sims, 0.286 more. For Upper Sims, MVE and SH both classified the entire site as canopy cover.

### 3.2. Reconstructed land use histories for each site

Below, we summarize the long-term change in land use and management and corresponding changes in land cover classes over time at our five field sites. Some sites have complex histories, reflected in both the imagery as well as the oral history and archival research. Other sites have less archival and/or oral information, resulting in heavier reliance on the imagery in order to learn about land use change history. We give brief narrative descriptions for each site based on field knowledge and interview/archival data, to complement the appropriate figures. We present examples of summary visualization figures for two sites (Fig. 2, *Táasich* and Fig. 3, *Tishánik*) and include the other three in Appendix B. In the summary figures, the images on top show the sequence of available aerial images, labeled by the year they were taken. The next panel below displays major land management and ecological disturbance

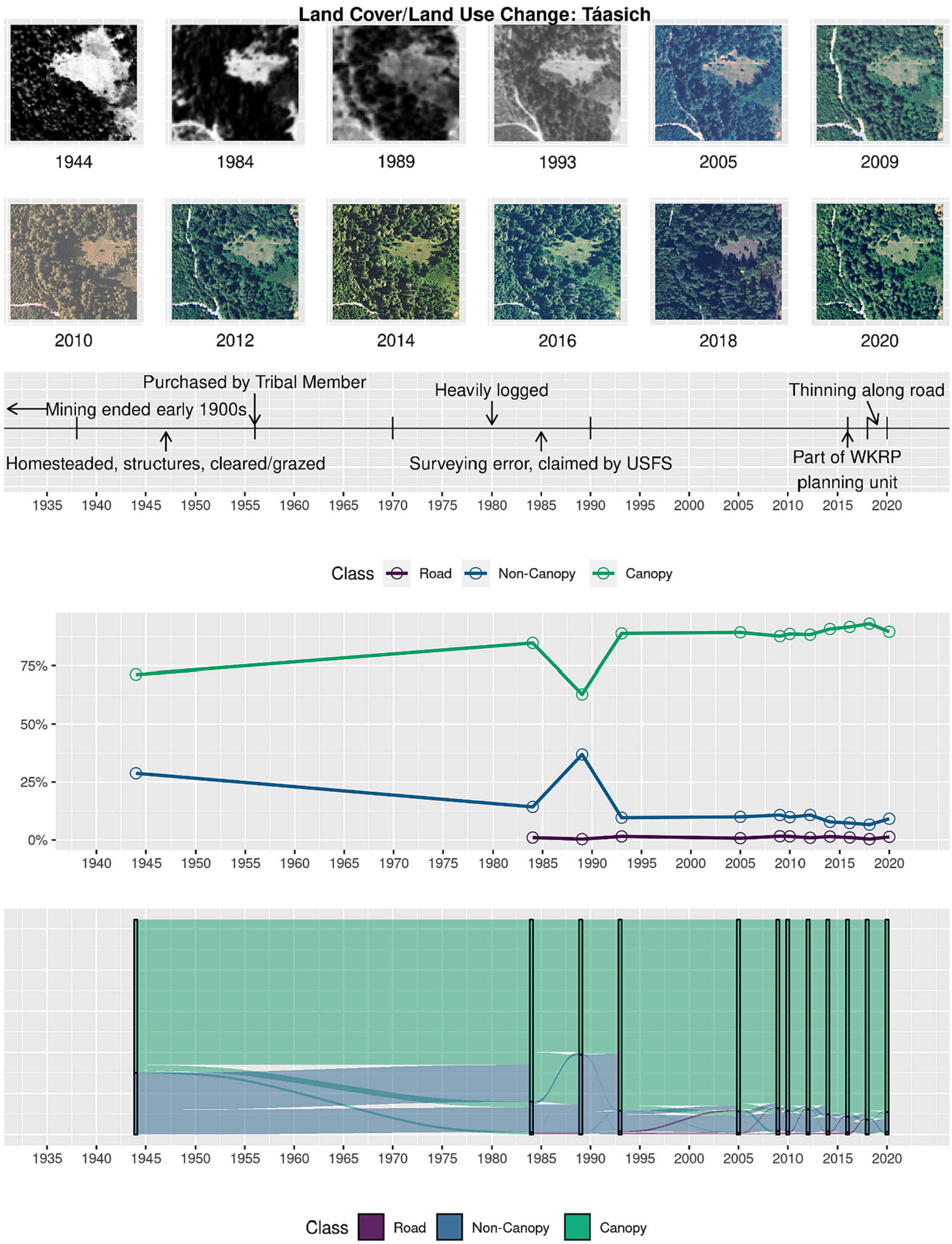


**Fig. 2.** Reconstructed land use and land change for *Táasich*. See text for more information. See supplementary materials for a time-lapse video of images over time.

events, represented in a timeline matching the figures below (tick marks indicate specific years or ranges of years). The third panel shows the overall changes in cover class over time, summarizing the proportion of the plot area classified in each year as canopy, non-canopy, or road. If there is no data point shown for a given class in a given year, the proportion was zero. The "alluvial" plots on the bottom panel show the individual transitions of specific locations in the site from one class to another over the years (because different pixels can change either way between two classes, bands often cross each other between years). Proportions in the bars at each image year should match the percentages

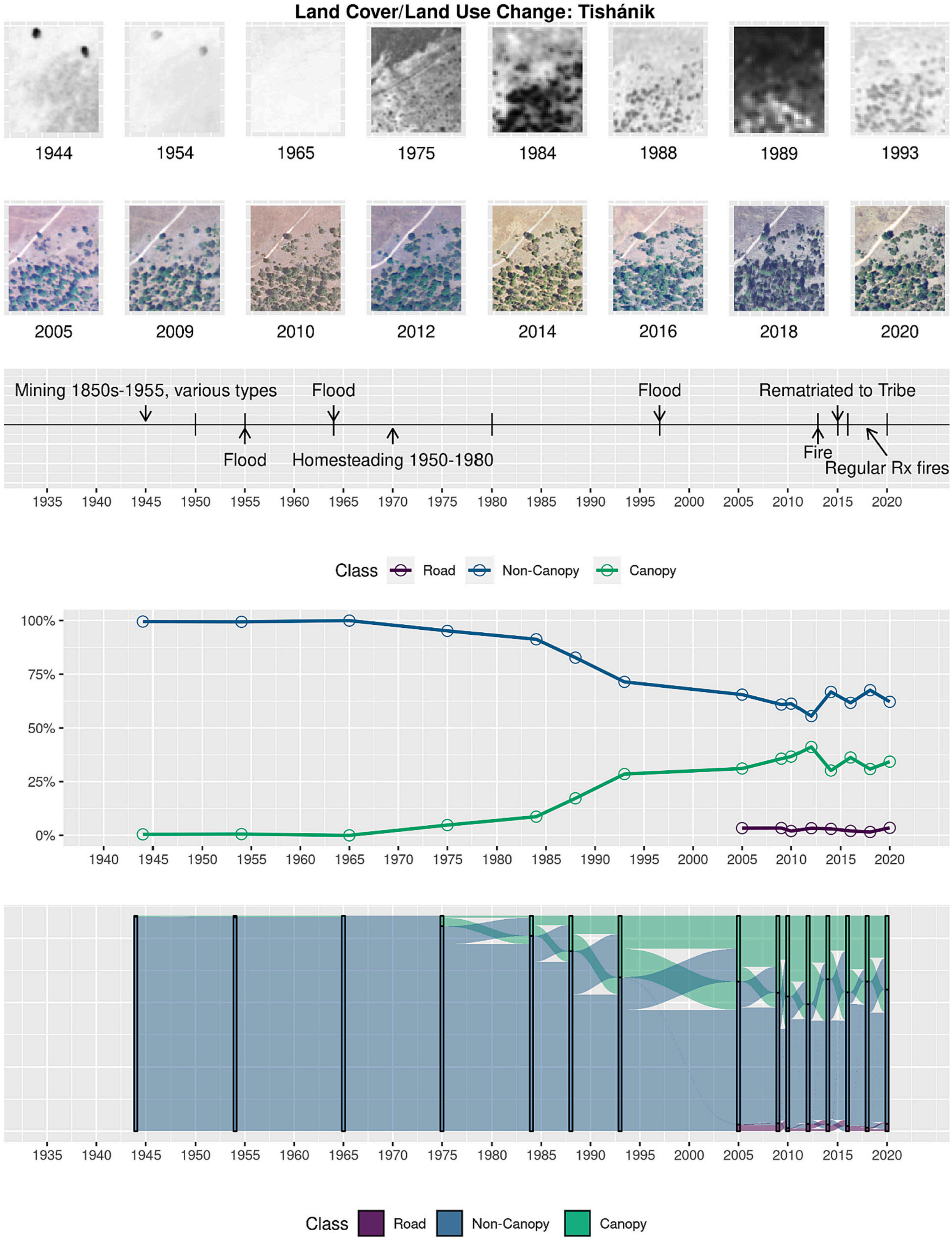


**Fig. 3.** Reconstructed land use and land cover change history at *Tishánik*. See text for more information. See supplementary materials for a time-lapse video of images over time.

shown in the figure above.

*3.2.1. Táasich - meadow maintenance and encroachment*

For *Táasich*, the meadow was maintained by homesteaders (likely through burning and/or grazing) by the time the first aerial photo was taken in 1944, but canopy cover had encroached significantly by 1984, likely due to lack of burning and thinning (Fig. 2; see Karuk Tribe-UC Berkeley Collaborative, 2023 for more information). Logging roads had been built into this area in this period between 1944 and 1984. The meadow opened back up slightly between 1984 and 1989, but the surrounding woody vegetation has been slowly encroaching into the meadow ever since, though there is a slight decrease in canopy cover in 2020, largely due to road maintenance. The surrounding area was heavily logged in the 1970s and 1980s (see later images of larger areas, e.g. Fig. 5, where the logging is more apparent).

#### 3.2.2. *Kámmaahriv – clearing and pile burning visible from imagery*

For this specific area, very little historical land use data was available, so the timeline largely reflects what is visible in the images themselves (see Appendix B for the full-page figure). The knoll was clear cut, save for a few legacy tan oak and chinquapin trees, and logging roads were built to remove timber between 1944 and 1984, likely in the 1960s–70s based on ethnographic accounts. The amount of canopy cover decreased again between 1984 and 1989, likely due to more logging. Since 1989, the amount of canopy cover has increased and non-canopy area has decreased steadily, with the exception of 2005–2009, likely due to thinning and fuels treatments/prescribed burning and pile burning in those years. There were additional thinning and pile burning activities conducted in 2020.

#### 3.2.3. *Tishánik - flood followed by frequent prescribed fire*

There was a large flood in 1964, denuding the floodplain completely of all vegetation (Fig. 3). Before the flood, there were two patches of “Canopy” (probably taller trees) which were then completely absent while other vegetation types re-established, and then “canopy” cover re-established steadily after, with manzanita shrubs and other woody vegetation taking over herbaceous cover, with the exception between 2012 and 2014, likely due to the fire in 2013. Frequent prescribed fires have kept “canopy” at a relatively steady state since the site was rematriated to the Tribe in 2015. Note that the 1989 image, though displayed, is not included in the analyses below due to the poor quality of the image.

#### 3.2.4. *Lower Sims - selective logging and recent prescribed fire*

The aerial images (see Appendix B for the full-page figure) show the “canopy” cover growing consistently since 1944, with the exception of 1975–1984 (likely due to selective logging and the building of the G-O road) and 2014–2016 (likely due to thinning and prescribed burning in the unit). Additional prescribed burning continues to reduce the canopy cover in this site from 2016 to 2020.

#### 3.2.5. *Upper Sims - logging followed by canopy cover recovery with no fire*

The cleared area around the former mining ditch tender’s cabin can be seen in the center right of the 1944 aerial image (see Appendix B for full-page figure). The logging activities of the 1960s and 1970s converted much of the land cover from “canopy” cover to open area/”non-canopy” cover, especially in the northwest corner of the plot. The site remained fairly open through 1993 and has rapidly converted to canopy cover since then: Douglas fir, planted redwood and some remaining legacy black oaks now cover nearly the entire plot.

### 3.3. *Canopy cover vegetation post-disturbance recovery rates*

Many of the images showed a trajectory of recovery with rapid infill in early years followed by slowing recovery as “canopy” effectively covered all available area (Table 2). Average recovery rates from fire and logging are similar in magnitude, while recovery of “canopy” from flood is much slower. The outlier is *Táasich*, which had a much faster recovery in “canopy” growth after logging, but this may be due to natural water seeps on that site resulting in a forested slope wetland habitat that could theoretically recover more quickly than other areas.

### 3.4. *Qualitative assessment of landscape change in surrounding areas*

Corroborating our quantitative calculations, the larger areas around our sites show similar patterns (note that each of the following figures includes one or more of our five sites). Recovery of “canopy” cover from fire is rapid (see Appendix B), e.g. from 2014 to 2020 (6 years), though field studies tell us the species composition may not be desirable (for example, large even-aged stands of Douglas-fir with reduced biodiversity and ecocultural value). Similarly, recovery from logging is somewhat rapid, and the images of the larger areas around our field sites give us a more detailed picture that parallels the archival research: from a timber management plan, we know that in the center of Fig. 4, half of

**Table 2**
For each site, recovery rates in hectares per year for “canopy” cover from disturbances of various types. For disturbances with multiple images recording a trajectory of recovery, we calculate both the “instantaneous” recovery rate between pairs of images, as well as the average recovery across the entire time period until the next disturbance.

| Site | Year | Disturbance type | Difference in area (ha) | “Instantaneous” rate (ha/yr) | Average rate (ha/yr) |
|---|---|---|---|---|---|
| Lower Sims | 1984–1988;<br>1988–1993 | Logging | 0.296;<br>0.009 | 0.074;<br>0.002 | 0.034 |
| Upper Sims | 1988–1993;<br>1993–2005;<br>2005–2009 | Logging | 0.075;<br>0.830;<br>0.092 | 0.015;<br>0.069;<br>0.023 | 0.048 |
| *Táasich* | 1989–1993 | Logging | 1.227 | 0.307 | 0.307 |
| *Kámmaahriv* | 1989–1993;<br>1993–2005 | Logging | 1.2998;<br>0.174 | 0.325;<br>0.014 | 0.092 |
| *Kámmaahriv* | 2009–2010;<br>2010–2012;<br>2012–2014;<br>2014–2016 | Fire | 0.169;<br>0.055;<br>0.129;<br>0.030 | 0.169;<br>0.028;<br>0.064;<br>0.015 | 0.055 |
| *Tishánik* | 2014–2016 | Fire | 0.058 | 0.029 | 0.029 |
| *Tishánik* | 1965–1975 | Flood | 0.046 | 0.005 | 0.005 |

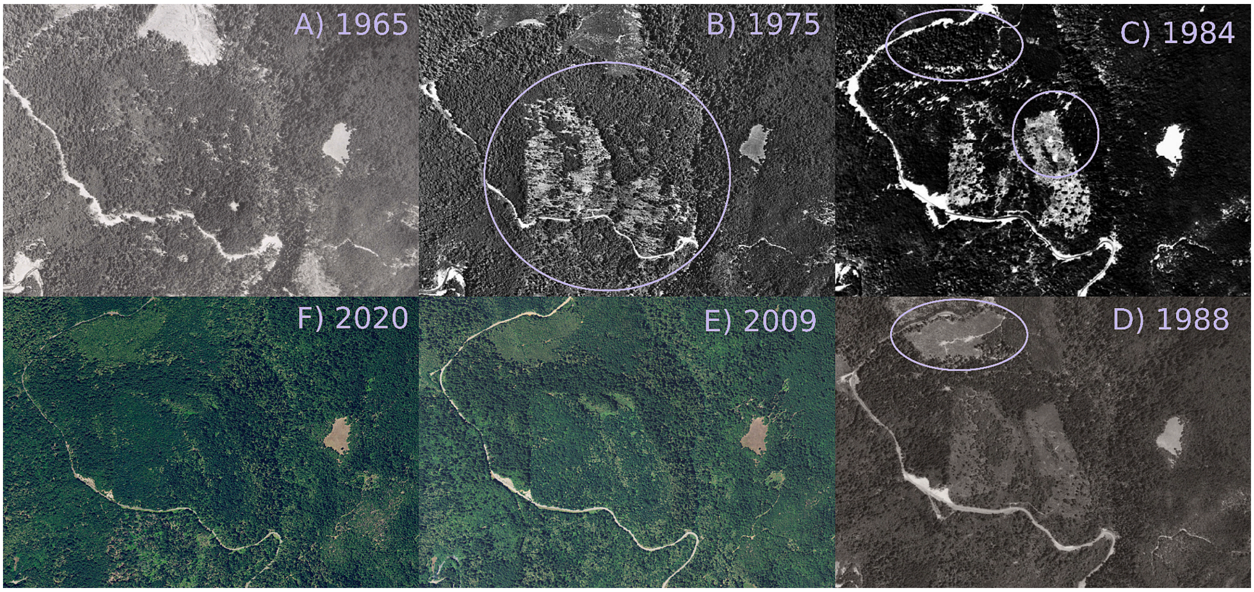


**Fig. 4.** Logging recovery. Images along with a timber management plan help us reconstruct the land use story of this area: A) in 1965, "high-grading" is not visible in the image while B) by 1975, heavier logging is quite visible inside the circled area. C) in 1984, all the removal indicated in the timber management plan between 1968 and 1978 has been completed (including circled additional removal in the northeast), and in D) 1988 a clearcut was done to the north of the timber management plan area (circled in both the 1984 and 1988 images). Both areas that were cut are still visible in E) 2009, but the central area has become largely re-forested in F) 2020. See supplementary materials for a time-lapse video of images over time.

this area was "selectively harvested in a manner that removed suitable timber trees for lumber between 1955 and 1968" (also known as "high-grading" and likely referring to commercially valued conifers such as Douglas-fir and sugar or ponderosa pines) and then between "1968 and 1978, an additional acreage of about 60 acres was harvested using a mix of heavy removal and selective harvest methods." In 1965, the selective logging mentioned in the timber management plan does not have a visible impact (as compared with 1944), while in 1975 the heavier logging is clearly visible. In 1984, the image shows the full extent of the management described, as additional areas have been cut to the east. Further north, in 1988, a clearcut has completely denuded the landscape. In 2009, the clearcuts are both still visible, while in 2020, much of the area in the center of the image has recovered, though the denuded clearcut to the north is still quite visible due to a difference in vegetation (likely even-aged Douglas-fir).

Even with no timber management plan for reference, we can still see in a different area to the north that what was fairly continuous canopy in 1944 had been thoroughly cut by 1989 but much of the cover has recovered by 2012 (Fig. 5).

The floods which swept away much of the vegetation along the Klamath river corridor in 1964 did remove some canopy cover, but various kinds of vegetation recovered within the first 10 years (1975) and canopy cover began to recover even by 1984 (see Appendix B and Fig. 3).

Finally, mining has left the most persistent geomorphic and vegetative effect on the landscape. For example, in the area shown in Fig. 6 below, extensive mining began in 1852 when small creeks were rerouted for hand sluices. Large ditches were constructed in the 1880s and incorporated into a system of 15 miles of ditches, flumes and tunnels that serviced four Orleans Bar Gold Mining Company hydraulic mines until mining operations and ditches were abandoned in 1912. In the 1944 aerial image shown below in Fig. 6, bedrock exposed by hydraulic mining remains denuded of soil and vegetation, as well as over 100 years post-mining in the 2020 image. We are unaware of additional management that would have prevented regrowth.

## 4. Discussion

Our method for piecing together diverse sources of historical data enabled a better understanding of historical ecological conditions and ecosystem change over time in and around our study sites, despite the sparseness of written information on historical land use and management. By working closely with our Indigenous community partners we were able to better understand the broader story of the landscape ecology and bring together all of the existing knowledge and information in order to reconstruct the story of these sites. Identifying the

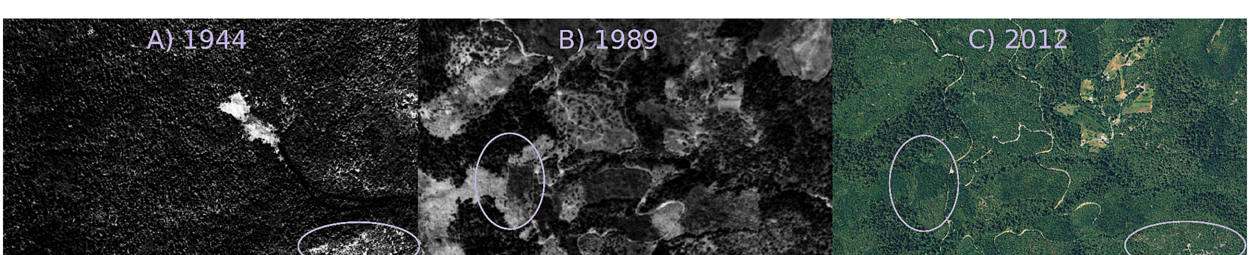


**Fig. 5.** Logging recovery. Aerial image sequences help us reconstruct the story of this area, which was largely forested in A) 1944, was thoroughly logged by B) 1989, and canopy cover has filled in almost all gaps by C) 2012. Notice how the legacy of logging in B, with three intensities of removal (complete, partial, and none) persists in C. The area in the lower right has retained gaps from the 1940s into the 2010s and 2020s, indicating a possible place for further research into historical land use. See supplementary materials for a time-lapse video of images over time.

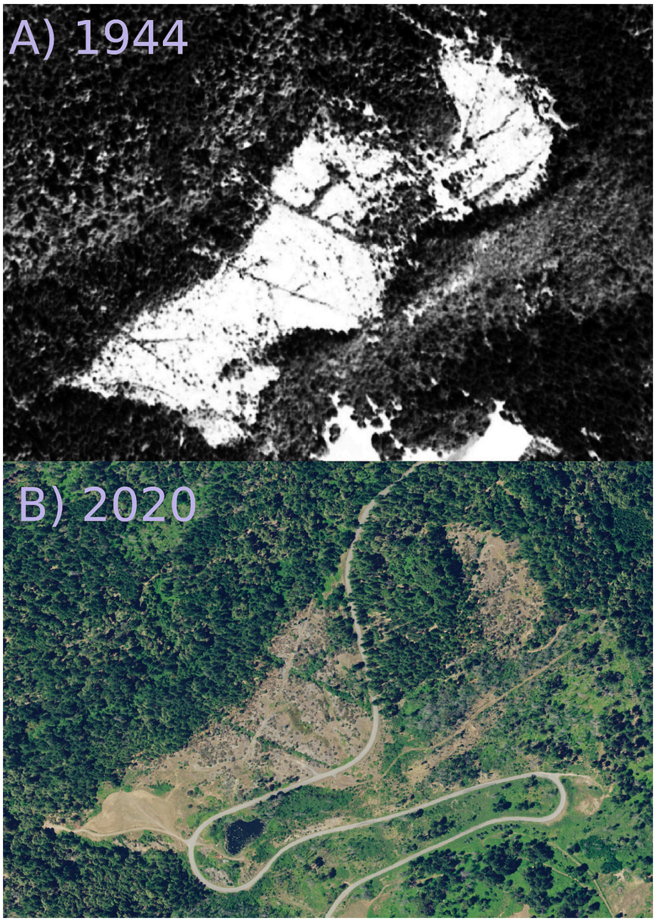


**Fig. 6.** Much slower recovery from mining between A) 1944 and B) 2020. See supplementary materials for a time-lapse video of images over time.

changes in ecosystem response to different management actions, land use patterns, and disturbances such as fires, floods and droughts has helped to support ecocultural restoration goals.

### 4.1. Advantages and drawbacks of analytical mixed-methods historical ecology

One advantage of this approach was the way in which the ethnographic and archival information and the classified historical imagery could be used iteratively to collectively reconstruct the history of change at a given site. In some cases, the ethnographic information informed how we interpreted the images, and in other cases, the images inspired questions for our community partners. Where there was a lack of one type of information (e.g. archival), another type of information could often fill in (e.g. imagery or oral history). Sometimes the imagery provided surprisingly detailed temporal information: in one case we could identify the timing of a particular logging clear cut (between 1984 and 1988) because it was not visible in 1984 but was in 1988 (Fig. 4). And the qualitative evaluation of the larger landscapes allowed us to visualize information in the archival research: Fig. 4 shows us what "50% thinning" from the timber management plan meant on the ground.

However, there are disadvantages to the manual delineation method we used for classification, largely that it was labor-intensive, which impacted the quantity of imagery we could classify as well as our validation methods. Having two classifiers working together, one with knowledge of the imagery (M.V. Eitzel, MVE) and one with knowledge of the field sites (Daniel Sarna-Wojcicki, DSW), resulted in much more accurate classifications than a classifier working more independently (Sean Hogan, SH) – but this method took a large number of person-hours, as did the additional time for SH to validate the classification. Validation of the earlier images with ground truth information is rarely if ever attempted in historical ecology (though one could, for example, core and age individual trees to assess whether they would have been present in an earlier image).

Even moving from a "validation" framing (using Kappa) to a "reliability" framing (using Krippendorff's Alpha) was difficult because Alpha is intended for many different 'raters' and more than two independent classifications may be necessary in order to quantify classification reliability. This represents even more labor. If this could be overcome, however, using Krippendorff's Alpha could be a way to quantify the reliability of the classifications of the earlier images. This could be valuable because individual images vary considerably in how clearly they can be interpreted and therefore how accurately types of disturbances can be ascribed. For our analysis in particular, it would be valuable to assess the Alpha as well as the differences in the areas of different classes for the images in which we wanted to measure change from year to year – essentially an assessment of how large an effect the different raters had on the quantitative output of the method. In this study, where we were exploring the method of multiple classifiers/analysts, we used Krippendorff's original ranges to decide what constituted sufficient agreement. This was partly because there are no universal ranges established, and in general appropriate agreement levels will vary for different applications and domains (Goldstein et al., 2021). Therefore, for future applications, discussion of what constitutes 'good enough agreement' is necessary.

Finally, even if uncertainty can be quantified in all stages of analysis, which we attempted to do (see Appendix B), a method needs to be developed to incorporate all these sources of uncertainty into the final result (Comber et al., 2012). In the end, it was only possible to qualitatively connect our results back to ground truthing data. This was enough for our purposes but future work may be able to improve on the accuracy of the analysis as well as the propagation of uncertainty.

### 4.2. Potential improvements for mixed-methods analytical historical ecology

There are multiple directions to develop the methods we illustrate here. We have shown larger-area images and videos showing the qualitative persistence of different types of management features in the landscape from a broader geographic field of view than just the individual research plots. Some of these changes could be assessed more quantitatively; however, the georegistration for the larger areas was considerably less precise than that at the research plots. One option would be to do a coarser georegistration for additional historical images, and to manually draw much coarser polygons depicting clearcuts, clearings from mining, and other similar persistent features. For the more recent NAIP imagery which is already georegistered, only the polygons would need to be drawn. Similar validation methods could be used, with Kappa used for imagery that can be ground-truthed, and Alpha used between multiple analysts classifying these areas of interest. This strategy represents a compromise between extremely detailed, precise analysis and broader, more qualitative investigation of change. In addition, the pixel size used for the 'alluvial' plots affects the visualization of change over time, so sensitivity to pixel size could be a useful check to perform (Eitzel et al., 2016).

Perhaps more promising, however, are emerging methods that incorporate the human ability to see patterns with machine learning methods used for classification, for example "human in the loop" classification (Buscombe et al., 2022). This could speed up the classification of larger areas, and might also enable finer classification of woody vegetation, especially in the NAIP imagery. This method could be particularly successful using the four-band spectral information in the images from 2009-present to try to differentiate vegetation types. Another possibility would be to use the Normalized Difference Vegetation Index (NDVI) for the four-band imagery to aid in classification.

There may also be ways to include information from online spectral libraries or other remote sensing products with more detailed spectral information and coarser spatial detail to refine classifications with the help of machine learning tools. We do caution, however, that though machine learning methods have great potential for automatic or supervised classification, they are still limited by the quality of their inputs (both imagery and training data): using NAIP and massive training datasets, they can perform well, but they may not succeed for historical imagery with its wildly variable characteristics (e.g. blurriness, distortion). More testing is necessary.

### *4.3. Classification scheme choices represent tradeoffs between qualitative and quantitative analysis*

Even within our manual classification method, there are options for richer analysis. We review our approach to arriving at the existing broad classification, but also demonstrate below how a finer classification may be possible (and desirable) for individual sites or images.

Each image (especially the historical images) differ substantially, so a classification scheme that was consistent enough across the different images was necessarily highly simplified. Over the course of our initial classification attempts, we considered "large canopy" versus "small canopy" based on crown diameter (but then found that these could not be consistently defined from image to image) and "woody" versus "herbaceous" versus "bare ground" (Fig. 7). In some images and at some sites we were able to make these kinds of distinctions. But the classification scheme that could be harmonized across all the sites and images was ultimately "canopy" and "non-canopy" – a classification that is in many ways unsatisfying given the richness of the images and qualitative information that we had compiled. One way of working with this tradeoff is to use multiple classifications, one that is simple and can be used for the quantitative comparisons we demonstrated in Section 3.3, and then for those sites where a more detailed classification is possible, to also examine the results of that classification as well. We demonstrate this with *Tishánik*, where examining the recovery from flood is much richer when observing the successional trading off of bare ground with first herbaceous vegetation and then with woody cover (particularly visible in the alluvial plot).

Of course, the understanding of these classified changes is also deepened by looking at the surrounding areas in a more qualitative way (as in Figs. 4–6), and by considering the narrative and qualitative knowledge we have collected at each site. Cultural practitioners interviewed during field visits shared their rich site-specific knowledge of place regarding historic land cover conditions, historical and contemporary management and land cover change over time – both pre-1944 imagery and from 1944-present, during the range of our imagery. A richer set of classifications would better support ecocultural management and reflect the potential of the dataset and community contributions.

### *4.4. Ecological insights supporting ecocultural restoration*

From an ecological resilience standpoint, we see that disturbances that affect the soil (mining or major floods) recover more slowly than either fires (prescribed or wildfire) or logging (both thinning and clearcutting). In a Clementsian succession sequence (Clements, 1916), these soil disturbances 'reset' the system so far back that each successional stage must play out in turn (this interpretation is clearest in the case of recovery from flood shown in Fig. 7). In the resilience framework, these disturbances may be so severe that the system has been pushed so far outside its typical disturbance regime that it may be in an alternative stable state (this is most clearly seen for mining recovery, Fig. 6). From an ecocultural resilience perspective, describing the regrowth of 'canopy cover' as 'recovery' is itself potentially problematic, because in the imagery we cannot distinguish species, and because canopy gaps are a proxy for understory diversity and health. If the forest

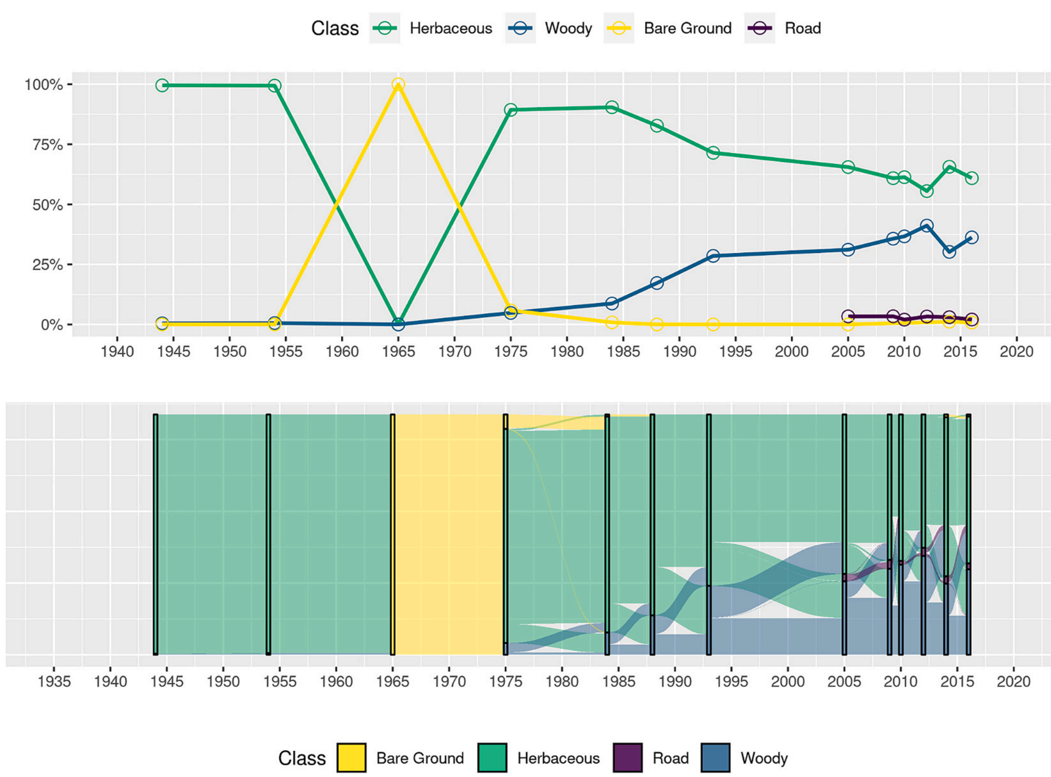


**Fig. 7.** Alternative classification for *Tishánik*. There was a large flood in 1964, denuding the floodplain completely of all vegetation. First herbaceous cover re-established quickly after the flood disturbance, then woody land cover re-established steadily after, with manzanita shrubs and other woody vegetation taking over herbaceous cover, with the exception between 2012 and 2014, likely due to the fire in 2013.

grows back but it is composed entirely of even-aged Douglas-fir, and there are no gaps for cultural use species to grow and thrive, then cultural resilience may suffer in parallel with the corresponding biodiversity loss, even when it seems the forest has 'recovered.'

KDNR managers and collaborators are in the process of planning and implementing fuels treatments including thinning and prescribed burning to restore habitats and cultural use species in all of the research plots (WKRP (Western Klamath Restoration Partnership), 2014). A better understanding of long term ecological change in these plots can help managers understand ecosystem responses to disturbances and strategize phased restoration prescriptions through time and at a landscape scale. For ecocultural managers, understanding these responses and recovery rates from different types of disturbances is helpful in planning landscape management treatments. For example, at sites where the Tribe has been applying prescribed fire or cultural burns (like Lower Sims and *Tishánik*, Fig. 3), managers may be interested in how the severity of burns may impact trajectories of forest structure and composition development post-treatment. More specifically, the range of canopy closure at a particular site may provide conditions that constrain or support important species in ways conducive to cultural uses, for example light availability for huckleberry production or shade cover for Pacific yew. Managers can see where recovery is faster at a particular site (for example, at *Táasich* in Fig. 2, where the seep wetland may support faster recovery than at other sites) or in response to particular disturbances. This mixed-method approach to conducting long term land use-land cover assessments grounded in local cultural knowledge of the landscape to inform ecocultural revitalization projects can hopefully serve as a model to help other Indigenous land stewards restore culturally important habitats and component cultural use species in Tribal lands and across jurisdictions of Tribal ancestral territory. Which components of the method are most appropriate to apply and most supportive of Indigenous ecocultural stewardship are areas for further place-based and community engaged exploration.

## 5. Conclusions

We conclude that the mixed-method approach we demonstrated can contribute significantly to ecocultural restoration planning for a team with access to historical and contemporary aerial imagery, local and traditional knowledge, and archival land management records of study sites. We were able to reconstruct ecological change over time and space and in response to different natural and anthropogenic disturbances. Ground truthing and assessing uncertainty is challenging, but land use histories can still be reconstructed across multiple sources of knowledge. Quantitative analysis must remain comparative between sites using similar imagery, not reflecting ground-truthed absolute changes, but is still valuable when paired with narrative and qualitative assessments of landscape histories. Potential tools that simplify the analyst's classification task but keep the "human in the loop" (Buscombe et al., 2022) may make these methods more feasible for more analysts and therefore may enable better quantification of classification reliability as well as expanding the total area that a team could classify. Managers can use the information about land cover change over time at these specific sites to guide their ecocultural restoration strategies, particularly where the information was sparse prior to analysis. The current approach was very labor intensive but may be worthwhile for small research plots, and allows the combination of a wide range of information into one analysis. Iterating between qualitative descriptions and images helps better understand place-based histories of land cover change, which is essential to supporting ecocultural restoration and resilience.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2024.102552.

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## CRediT authorship contribution statement

**M.V. Eitzel:** Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Daniel Sarna-Wojcicki:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Sean Hogan:** Formal analysis, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. **Jennifer Sowerwine:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Megan Mucioki:** Investigation, Resources, Writing – review & editing. **Kathy McCovey:** Investigation, Resources, Writing – review & editing, Validation. **Shawn Bourque:** Investigation, Resources, Writing – review & editing, Validation. **Leaf Hillman:** Investigation, Resources, Validation, Writing – review & editing. **Lisa Morehead-Hillman:** Investigation, Resources, Validation, Writing – review & editing. **Frank Lake:** Investigation, Resources, Validation, Writing – review & editing. **Vikki Preston:** Investigation, Resources, Validation, Writing – review & editing. **Chook-Chook Hillman:** Investigation, Resources, Validation, Writing – review & editing. **Andy Lyons:** Conceptualization, Methodology, Writing – review & editing. **Bill Tripp:** Investigation, Resources, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare no conflicting interests. All opinions, findings, and conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the university or Tribe, and should not be construed to represent any official USDA or US government determination of policy.

## Data availability

Due to Tribal research policy requirements, the data that support the findings of this study are not publicly available beyond current appendices. Data requests can be made through the Karuk Tribe's research coordinator and should follow Karuk Practicing Pikyav Tribal research requirements. For more information, see: https://nature.berkeley.edu/karuk-collaborative/?page_id=165.

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